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Metallurgy and Ceramics

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General Electric Company
KNOLLS ATOMIC POWER LABORATORY
Schenectady, New York

✓ EMBRITTLEMENT OF MOLYBDENUM BY NEUTRON RADIATION

✓ C. A. Bruch
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R. W. Hockenbury

March 1, 1954

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United States Atomic Energy Commission
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ABSTRACT

Commercially pure molybdenum specimens were irradiated in the MTR for an estimated exposure of 1.9 to 5.9×10^{20} thermal nvt. Prior to irradiation, the material was ductile in the tension test, whereas after irradiation it was brittle. The results of tension tests conducted at various temperatures revealed that the transition temperature for this material had been increased for -30°C to $+70^{\circ}\text{C}$ as a result of the radiation exposure. From metallographic studies it is concluded that the embrittlement is due to submicroscopic changes which raise the flow curve of the material. The results presented show that commercially pure molybdenum is an unsafe material for low-temperature (below 100°C) use in load-carrying reactor components.

EMBRITTEMENT OF MOLYBDENUM BY NEUTRON RADIATION

C. A. Bruch, W. E. McHugh, R. W. Hockenbury

I. INTRODUCTION

A brittle metal can be used successfully as a load-carrying structural member provided that the designer can take into account all of the service conditions; however, if service conditions are more severe than anticipated, the part may fracture. It is much safer to use ductile metals, because under unusually severe conditions these metals will usually deform without fracture and the stresses will thereby be redistributed.

Probably the most dangerous types of structural metals are those that either behave in a ductile fashion under some conditions of loading and are brittle under other conditions or those that during the service life undergo metallurgical changes which render them brittle. This report is concerned with molybdenum, a metal which ordinarily falls into the first category and which also falls into the latter category when subjected to neutron radiation.

Molybdenum is prepared commercially by either powder metallurgy techniques or by vacuum arc-melting and casting techniques. Bechtold¹ has shown recently that it is possible to fabricate ingots of the same approximate chemical composition, manufactured by either process, into wrought products that have approximately identical tensile properties. He showed that both wrought materials exhibit a transition temperature* very close to room temperature in the tension test. The transition temperature for the arc-cast material was about 10°C higher than that for the sintered powder material. He also demonstrated that variations in grain size markedly affect the transition temperature. Some of his data are reproduced in Figure 1, which shows the effect of temperature and grain size on both the yield strength and per cent reduction in area of molybdenum prepared by powder metallurgy techniques. Although there are many criteria for determining the transition temperature,² for the present purpose it will be selected as the inflection point in the curve drawn for per cent reduction in area versus temperature. For all of these curves in Figure 1, the inflection point occurs at approximately 40% reduction in area. It is shown quite clearly in Figure 1 that the material has a transition temperature which increases with increasing grain size, and is well above room temperature for material having 100 grains per square millimeter.

Since the transition temperature in the notched bar test is significantly higher than that for simple tension tests for many other metals,^{3,4} these results indicate that load-carrying structural members made from commercially pure molybdenum are normally subject to brittle fracture if operated near room temperature.

*A discussion of the transition temperature phenomenon is given in the Appendix.

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Other investigators^{5,6} have studied several commercial steels and found that these were embrittled by neutron radiation. For these steels, the increases in transition temperature as determined by notched bar impact tests range from 65 to 100°C after an exposure of 9×10^{19} estimated fast nvt.

The results which follow demonstrate the fact that molybdenum of commercial purity is also embrittled by neutron radiation.

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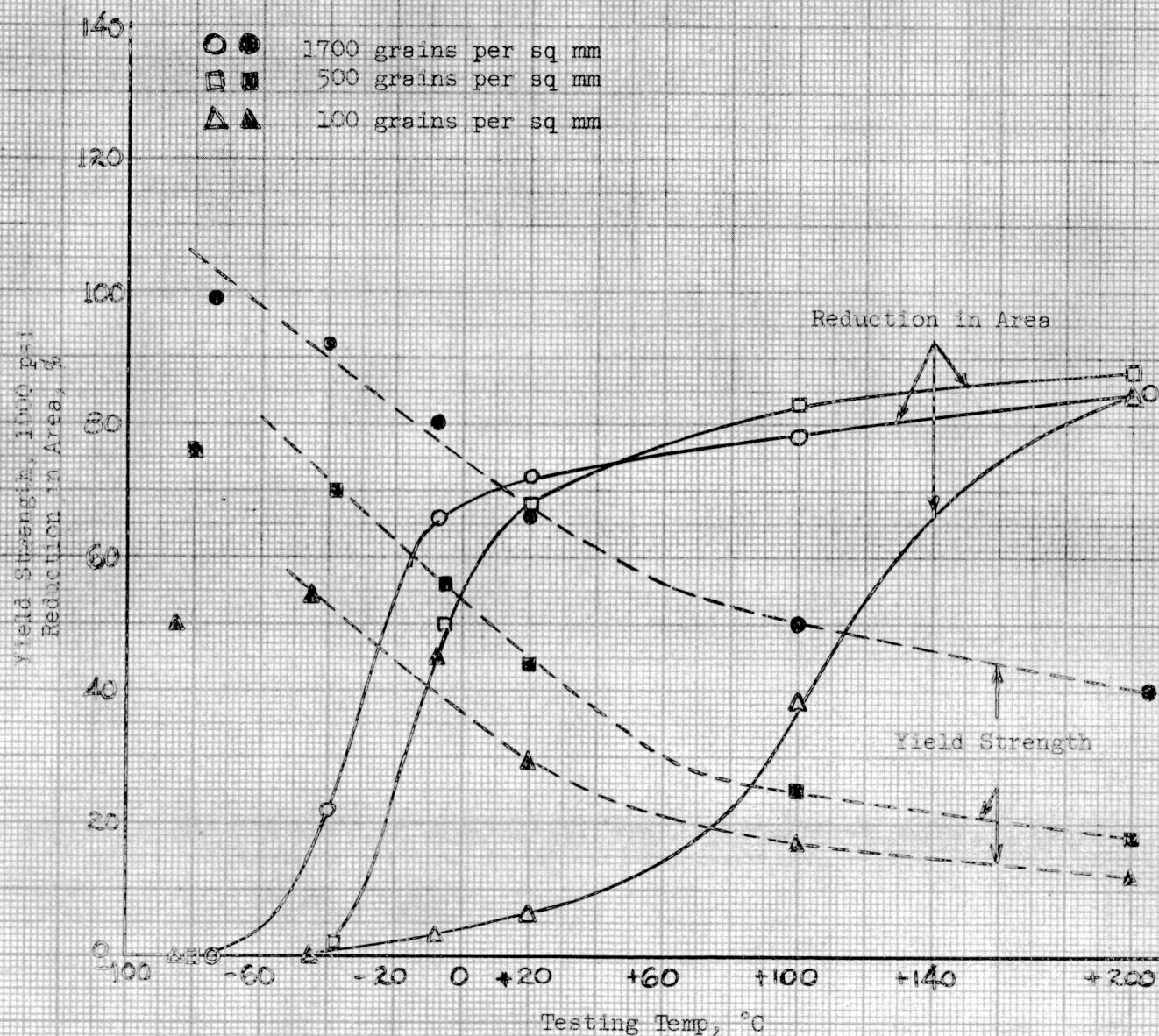


FIGURE 1

THE EFFECT OF GRAIN SIZE AND TEMPERATURE ON BOTH THE YIELD STRENGTH AND PER CENT REDUCTION IN AREA OF SINTERED MOLYBDENUM (Bechtold¹)

II. EXPERIMENTAL PROCEDURES

A comprehensive experimental program is under way at KAPL to determine the effect of neutron irradiation on the mechanical properties of metals.⁷ The results being reported here represent only a small but significant part of the program, the object of which was to determine the effect of a short exposure in the MTR on the mechanical properties of molybdenum. All measurements were made before and after irradiation.

A. Material

The molybdenum used in this investigation was obtained from the Climax Molybdenum Company. The two heats from which the material originated were melted under a vacuum of 5 to 30 microns and cast in 7-inch-diameter, water-cooled copper molds. One heat contained 0.061%, and the other 0.066% carbon. Both heats were subsequently hot-worked by extrusion and rolling into 5/8-inch-diameter rods, after which they were annealed and straightened.

The material was subsequently heated to 1100°C in a hydrogen atmosphere and swaged to 1/2-inch-diameter rod at the Research Laboratory of the General Electric Company. The resulting material had an average hardness of 264 V.P.N. or 99.2 Rockwell B, and had an average of 5000 grains per square millimeter in the transverse sections. The grain structure in longitudinal sections varied. In some sections the grains were equiaxed and in others, elongated. Since annealing experiments showed that recrystallization did not occur even after 24 hours at 1200°C, and since the hardness numbers for both types of sections were essentially the same, it has been concluded that both types recrystallized in the swaging process.

B. Test Specimens

Substandard-size tensile specimens were prepared according to the specifications shown in Figure K-6A4647. These specimens were also used for hardness tests.

Metallographic specimens were polished, etched, and photographed at a magnification of 1000X prior to irradiation. The field studied was identified by means of a Knoop hardness indentation.

In addition to the specimens described, X-ray diffraction specimens and flux and temperature monitors were prepared. These have been described in detail elsewhere.⁷

C. Irradiation

Twelve tensile specimens, six metallographic specimens, and the additional X-ray diffraction specimens and monitors were enclosed in two aluminum capsules, each approximately 24 inches long. These were irradiated in active lattice position L-41 of the MTR and received an exposure of 663 megawatt-days. The loading schemes for the two slugs are shown in Figure 2, which also shows the approximate location of the horizontal center plane of the reactor and the

integrated thermal flux about the center plane as calculated using the data of Bright and Schroeder.⁸ As shown in this figure, the range of exposure varied from 1.9 to 5.9×10^{20} thermal nvt.

The integrated fast flux (neutrons with energy above 1 Mev) is not known at this time, but is estimated to be of the same order of magnitude as the thermal flux for this reactor position. It is planned that, at some later time, a more precise value for the integrated fast flux will be obtained from the flux monitor data.

D. Testing Equipment

Only a brief description of the equipment will be given, since most of it has been described elsewhere.⁷

A Rockwell hardness tester modified for remote operation was used for hardness testing.⁷ A special remotely operable metallograph was used for the metallographic examinations.⁷

Tensile testing was done using two machines. One was a standard hydraulic machine. Since this testing machine was used for tests of specimens immersed in liquid baths, no strain gauges were used.

All room-temperature tensile tests were done using a remotely operable horizontal testing machine and a remotely operable extensometer built at KAPL.⁷ This tensile machine has three load ranges: 1000, 4000, and 10,000 pounds. The extensometer has two active linear differential transformers. The signal from one activates a recorder which magnifies the extension of the gauge length of the specimen (approximately 0.75 inch) ten times; the signal from the other activates a recorder which magnifies the extension either 100 or 1000 times. Since the recorders were of the load-elongation type, two load-extension diagrams were recorded autographically and simultaneously.

Testing at other than room temperature was done by immersing the specimen in a liquid bath during the test. Acetone cooled by dry ice was used for low temperatures, and water heated by immersion heaters was used for the higher temperatures.

All tensile test values such as yield strength, per cent reduction in area, and so forth, were obtained by conventional methods.

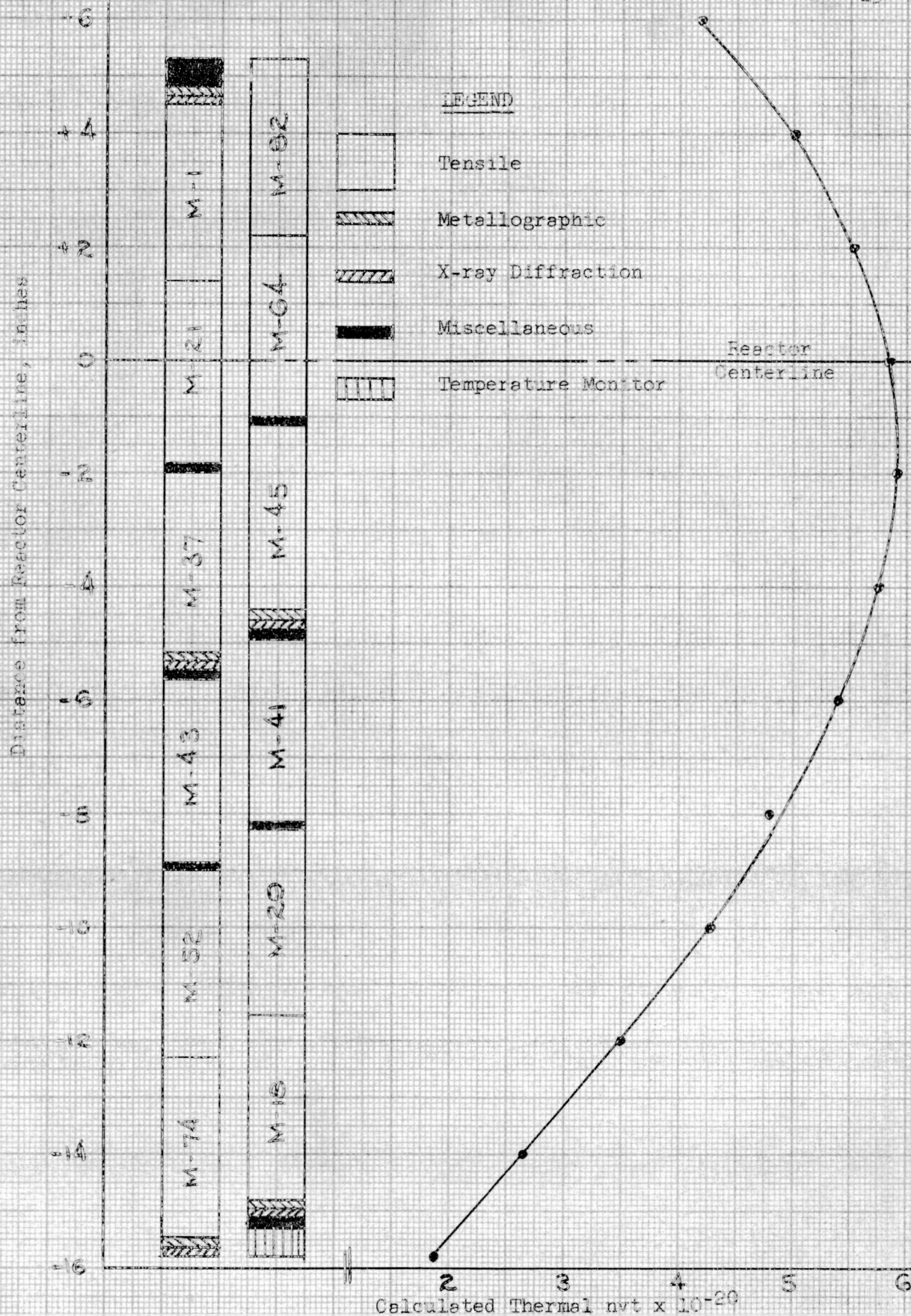


FIGURE 2

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SPECIMEN POSITION AND CALCULATED THERMAL NVT WITH RESPECT TO THE HORIZONTAL CENTER PLANE IN ACTIVE LATTICE

III. Experimental Results

A. Temperature Monitors

An examination of the various metals and alloys contained in the temperature monitors showed that the temperature of the specimens during the irradiation probably exceeded 70°C but did not exceed 95°C.

B. Metallographic Examination

In Photograph 1132962 are photomicrographs originally magnified 1000X of the same field for the following conditions: A, etched, prior to irradiation; B, same as A after irradiation; C, same as B except etched 30 seconds; D, same as C, except etched an additional 60 seconds. The etchant consisted of one part of 10% NaOH in water, and one part of 10% $K_3Fe(CN)_6$ in water.

Neither the photomicrographs nor the microscopic examination revealed any visible change in the microstructure as a result of the irradiation.

C. Hardness Testing

The results of the Rockwell C hardness tests taken on the flat ends of the tensile specimens are summarized in Table I. This table also gives Brinell hardness numbers, as converted from the Rockwell hardness measurements.

TABLE I

<u>Material Condition</u>	<u>Rockwell C*</u>		<u>Brinell Number</u>	<u>Rockwell A*</u>		<u>Brinell Number</u>
	<u>Avg Value</u>	<u>Min, Max</u>		<u>Avg Value</u>	<u>Min, Max</u>	
Unirradiated	23.0	19.7/24.9	242	62.0	59.9/63.0	243
Irradiated	28.5	24.2/31.7	275	64.9	62.8/66.5	280
Change	+5.5	+3.0/+7.7	+33	+2.9	+0.5/+4.4	+37

*Each number in the table represents the average of test results for twelve specimens. At least three Rockwell hardness measurements of each kind were made per specimen.

As a result of the irradiation, the molybdenum hardened by approximately 35 Brinell numbers. No correlation was found between the hardness increase and the position of the specimen with respect to the reactor horizontal center plane. In other words, the amount of hardening was independent of the integrated thermal neutron flux in the range studied.

D. Tensile Testing

Twelve specimens were tested at various temperatures. Five specimens were unirradiated, five were irradiated, and two were unirradiated but "aged" for 30 days at 90°C, to simulate the thermal history of the irradiated specimens. Complete load-elongation curves were obtained for the tests which were conducted at room temperature, whereas only a limited amount of data was obtained for each of the other six specimens tested in liquid baths.

In Figure 3 are load-elongation curves for two irradiated and two unirradiated specimens which were tested at room temperature. These curves show that, prior to irradiation, the material had a sharp yield point and considerable ductility as measured by elongation. After irradiation, the material was completely brittle, and each specimen fractured in two places. Multiple fracture of brittle materials has also been observed elsewhere.⁹

In Figure 4 are load-elongation curves for the two specimens which were "aged" at 90°C for 30 days; for comparison, the curves for the two unirradiated specimens are also included. It can be seen that the 90°C heating had very little effect, if any, on the tensile properties of the material. The results indicate that the "aging" may have slightly reduced the tensile strength and elongation, but these differences are not considered significant.

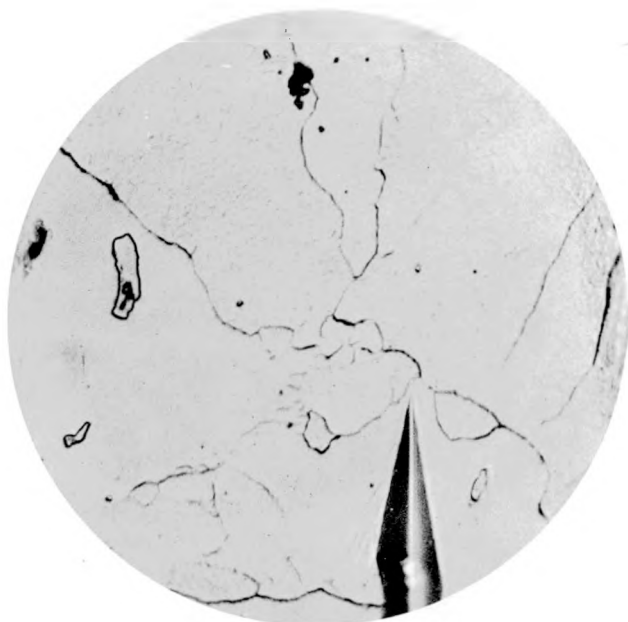
The data obtained from all of the tensile tests have been summarized in Table II. The following results appearing in this table are considered significant:

1. The unirradiated material was ductile in tests conducted at room temperature and at -20°C as evidenced by the relatively high values of per cent reduction in area and elongation, whereas at -40 and -60°C the material was completely brittle.

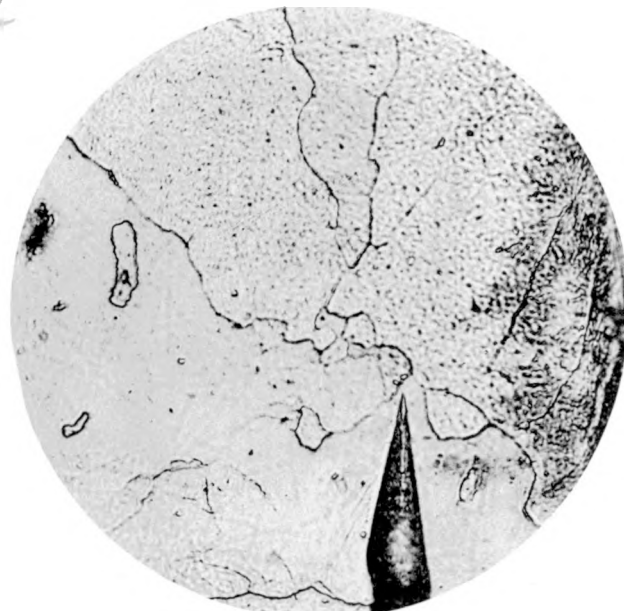
2. The unirradiated material "aged" at 90°C had essentially the same properties at room temperature as the unaged specimens.

3. The irradiated material was completely brittle in tests conducted at room temperature and at +60°C. At +80 and +100°C the irradiated material was ductile.

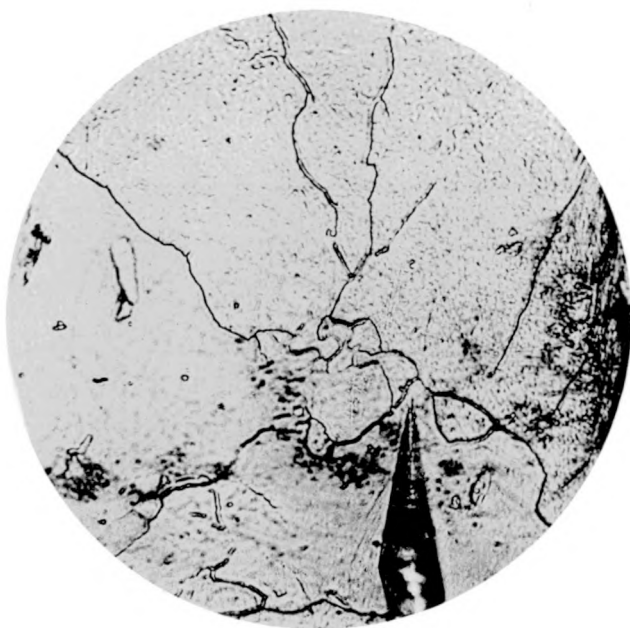
In Figure 5 are graphs of per cent reduction in area versus temperature for both the unirradiated and irradiated specimens. For comparison the data reported by Bechtold¹ are also reproduced here. The transition temperatures, as stated previously, are located at 40% reduction in area. Irradiation has changed the transition temperature from approximately -30°C to approximately +70°C, an increase of approximately 100°C. The transition temperature for the irradiated material is the same as for unirradiated material having approximately 200 grains per square millimeter.



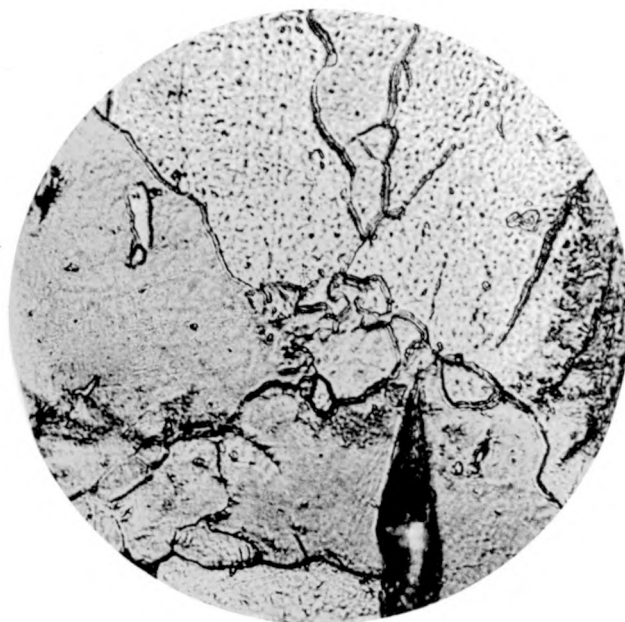
A



B



C



D

PHOTOMICROGRAPHS AT ORIGINAL
MAGNIFICATIONS OF 1000X OF THE
SAME FIELD FOR THE FOLLOWING CONDITIONS:

- A. Molybdenum Etched, prior to Irradiation
- B. Same as A after Irradiation
- C. Same as B, except Etched 30 Seconds
- D. Same as C, except Etched an Additional 60 Seconds

Etchant: One part of 10% NaOH in water, and one
part of 10% $K_3Fe(CN)_6$ in water.

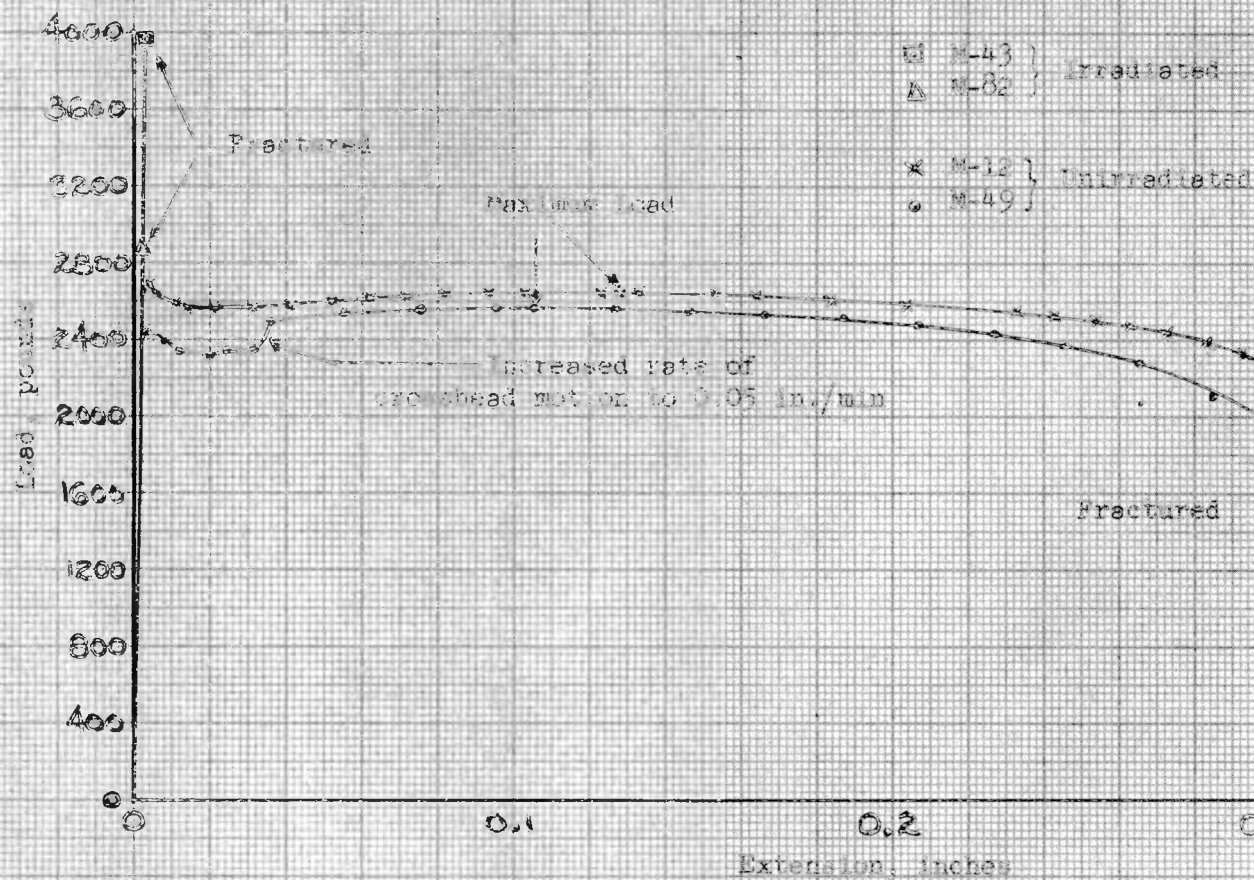


FIGURE 3

LOAD VERSUS ELONGATION FOR IRRADIATED
AND UNIRRADIATED MOLYBDENUM

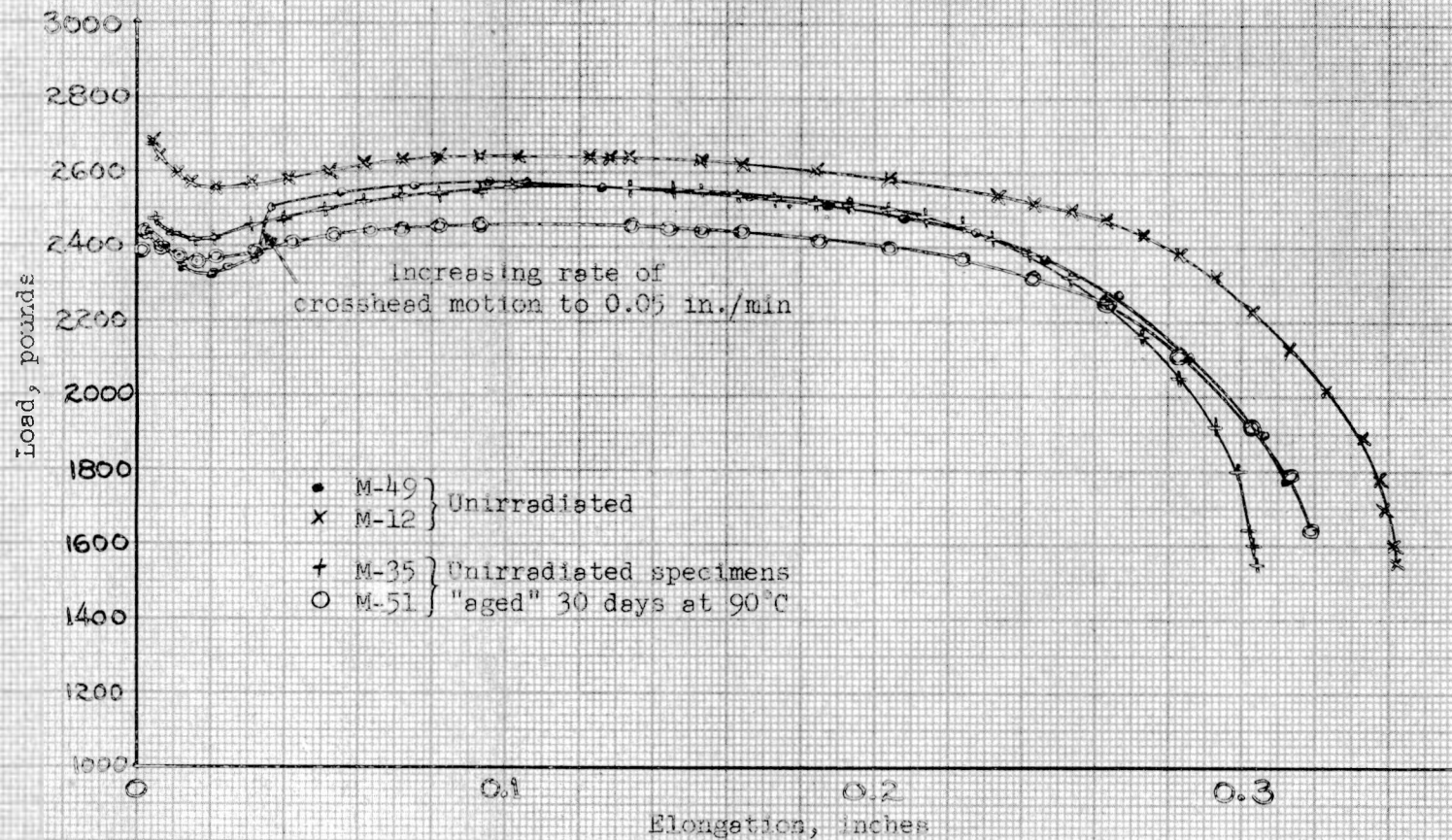


FIGURE 4

LOAD VERSUS ELONGATION FOR MOLYBDENUM "AGED"
AT 90°C FOR 30 DAYS, AND UNIRRADIATED MOLYBDENUM

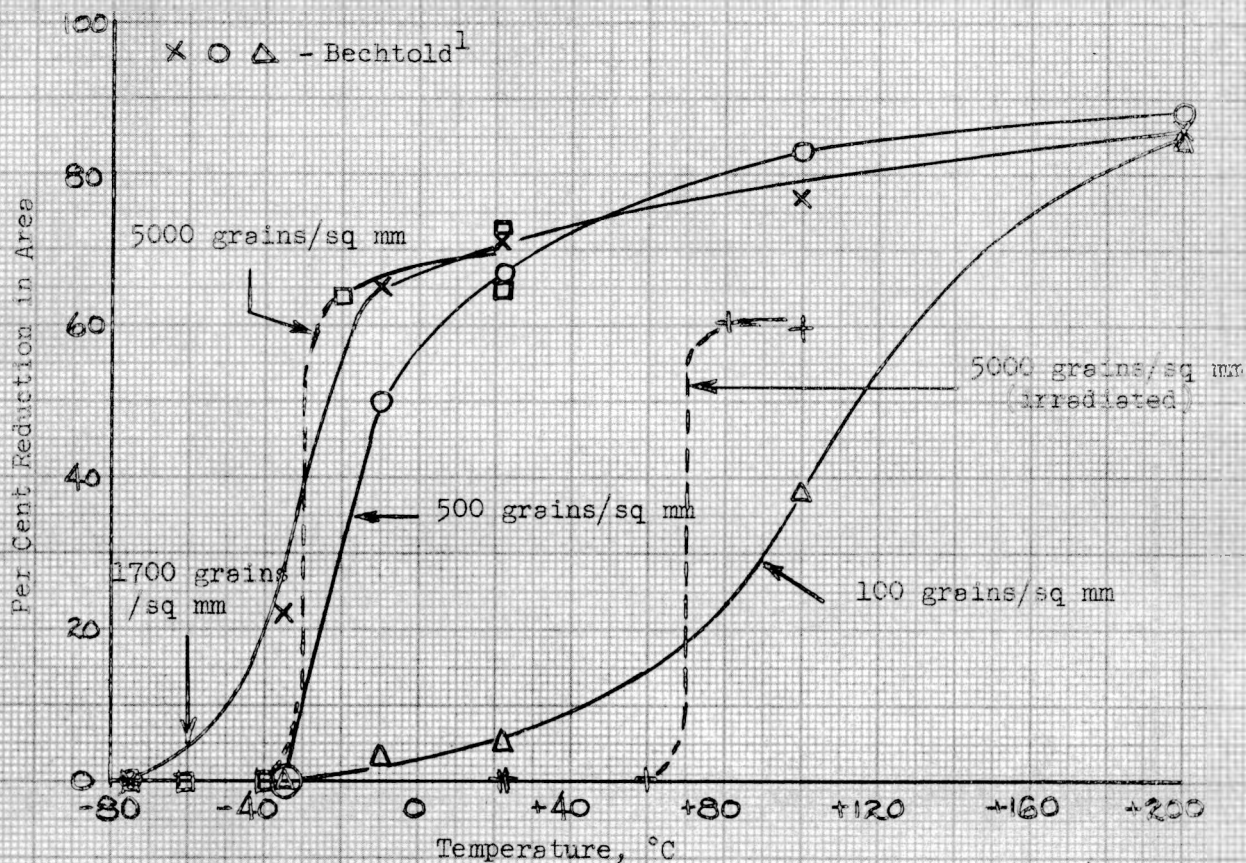


FIGURE 5
THE EFFECT OF TEMPERATURE, GRAIN SIZE, AND NEUTRON
RADIATION ON THE PER CENT REDUCTION IN AREA OF
MOLYBDENUM TENSILE SPECIMENS

TABLE II

<u>Spec Desig</u>	<u>Condition</u>	<u>Integrated Thermal Neutron Flux</u>	<u>Test Temp, °C</u>	<u>Upper Yield Point, psi x 10³</u>	<u>Tensile* Strength, psi x 10³</u>	<u>Fracture Stress psi x 10³</u>	<u>Per Cent Elongation</u>	<u>Per Cent Reduction in Area</u>
M-12	Unirrad	-	+22	102.5	100.8	214.0	45.7	72.4
M-49	Unirrad	-	+22	93.8	98.8	193.0	41.7	65.0
M-44	Unirrad	-	-20	125.5	120.0	243.0	32.8	63.8
M-58	Unirrad	-	-40	-	123.0	123.0	0	0
M-36	Unirrad	-	-60	-	142.0	142.0	0	0
M-35	"Aged" **	-	+24.6	94.4	97.7	182.6	40.8	67.4
M-51		-	+24.6	94.0	94.3	181.6	42.5	65.3
M-43	Irrad	5.1×10^{20}	+21.8	151.7	151.7	149.0	0	0.08
M-82	Irrad	5.1×10^{20}	+22.4	-	109.7	109.7	0	0
M-21	Irrad	5.85×10^{20}	+60	-	148.5	148.5	0	0
M-37	Irrad	5.85×10^{20}	+80.5	143.5	143.5	185.0	14.7	60.5
M-64	Irrad	5.8×10^{20}	+100	111.5	111.5	134.0	10	59.7

*Maximum load divided by original area.

**Unirradiated specimen heated for 30 days at 90°C.

IV. DISCUSSION

The commercially pure molybdenum used in this investigation was a normal material and comparable to that used by other investigators. For example, in Figure 6 are graphs of both the yield strength at room temperature and the transition temperature versus the reciprocal of the average grain diameter, using data reported by Bechtold¹ and those data obtained in this investigation. Curves have been drawn through the points and the agreement is good. The material used in this investigation behaves in the manner which would be predicted from the data of Bechtold.

The irradiation hardening was moderate, and as such, did not indicate the significant changes which had occurred in the room temperature tensile properties. Tabor¹⁰ has shown that there is a direct correlation between indentation hardness and yield stress; hence, an increase in hardness implies an increase in yield stress, a shift in the flow curve, and a possible shift in the transition temperature. However, in order to determine the effect of some variable on the transition temperature, it is necessary to use a destructive test such as the tension or notched-bar impact.

The results of the tensile tests show clearly that irradiation has further embrittled molybdenum in that the transition temperature increased from approximately -30°C to $+70^{\circ}\text{C}$. It has already been pointed out that this corresponds to a transition temperature for unirradiated molybdenum having approximately 200 grains per square millimeter. Since the material had approximately 5000 grains per square millimeter prior to radiation, and since metallographic examinations have shown that there were no microscopically visible changes in the structure, it must be concluded that the radiation embrittlement was caused by submicroscopic changes.

The gross effect of irradiation has been to change the relative position of the flow curve with respect to the fracture curve, implying that the ratio of the critical resolved stress for slip to that for cleavage has been increased. To illustrate this point, in Figure 7 are plotted yield stresses and fracture stresses versus temperature for irradiated molybdenum as well as unirradiated material having various grain sizes. Some of the data were obtained from Bechtold's results.¹ Two curves have been drawn for each condition of the metal, and these have been separated by a vertical line which represents the highest temperature at which the reduction in area of the test specimen was zero. The curve to the right of the vertical line is the yield stress or flow curve, that to the left is the fracture curve. The best average flow curves consistent with the limited amount of data were drawn through the yield-stress points. Average fracture curves were drawn through the fracture-stress points, and these were drawn horizontally because of the very limited amount of data. All points agree fairly well with the curves as drawn except the one for the irradiated specimen which had a fracture stress of 109,700 pounds per square inch at room temperature. This specimen showed a nonlinear behavior in the early part of the test. The reason for the behavior is not understood, although it may have been due to specimen misalignment or structural imperfections in the specimen. The data presented in Figure 7 show that both the

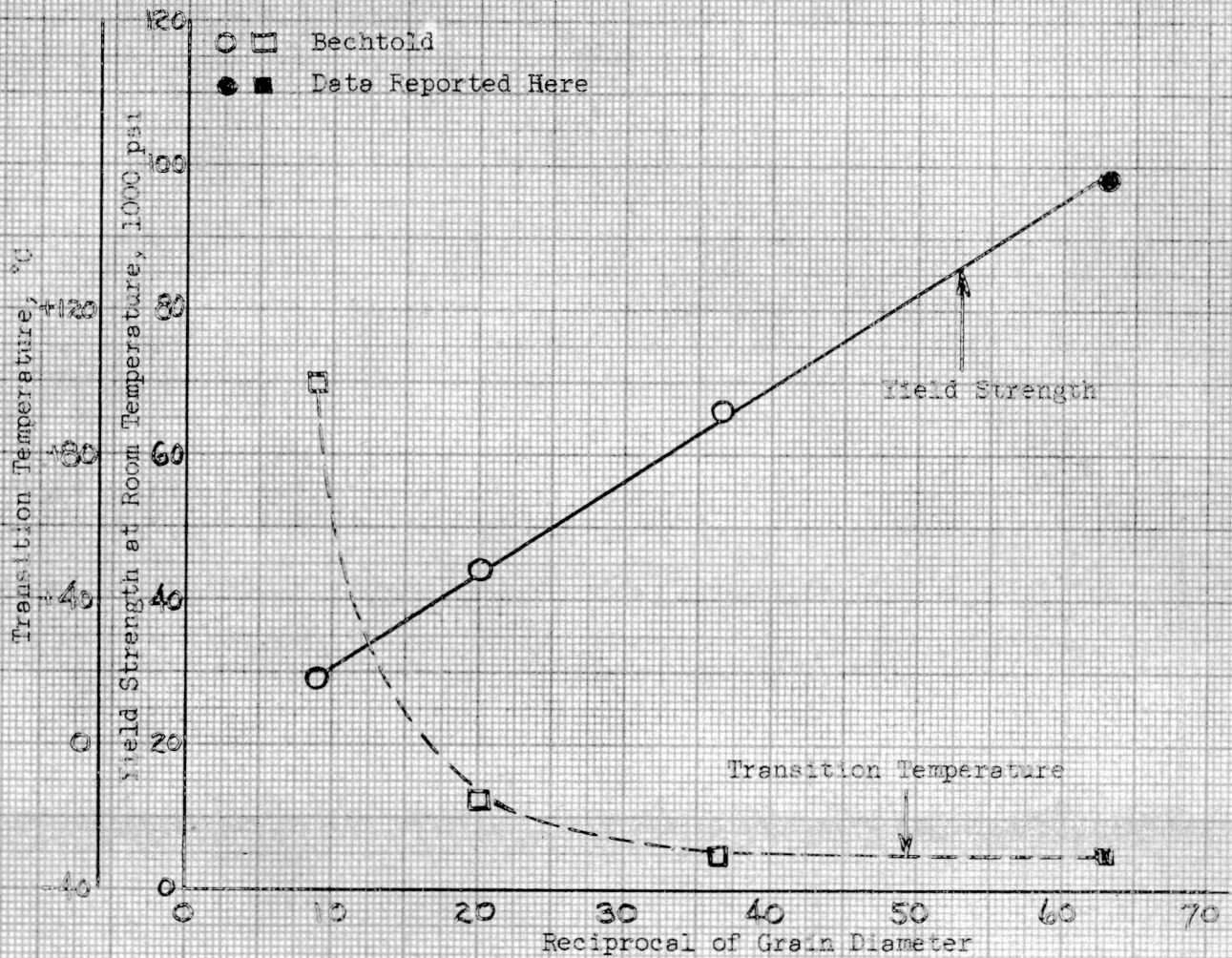


FIGURE 6

YIELD STRENGTH AT ROOM TEMPERATURE AND TRANSITION TEMPERATURE AS A FUNCTION OF THE RECIPROCAL OF THE AVERAGE GRAIN DIAMETER

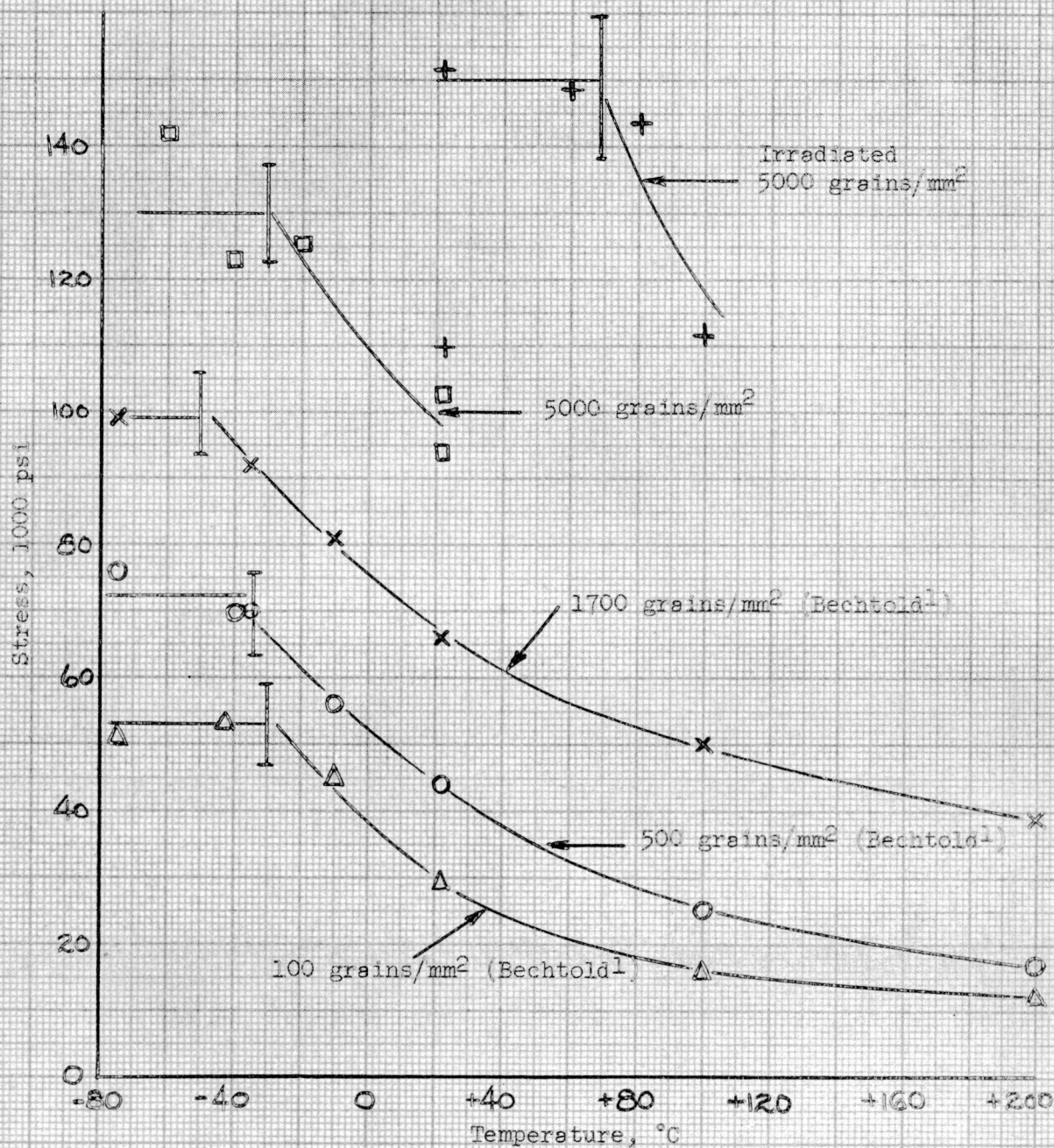


FIGURE 7

YIELD AND FRACTURE STRESS AS A FUNCTION OF GRAIN SIZE, IRRADIATION, AND TEMPERATURE. FRACTURE CURVES ARE TO THE LEFT OF VERTICAL LINES AND FLOW CURVES ARE TO THE RIGHT.

flow and fracture curves for unirradiated molybdenum are raised with increasing grain size, and that the effect is quite pronounced. They also show that the flow curve is appreciably raised by irradiation, and the indication is that the fracture curve is also raised, but to a lesser degree.

The mechanism by which irradiation causes a shift in these curves is not fully understood at this time. It is generally agreed that there are three types of defects produced in the metal lattice by neutron bombardment: lattice vacancies, interstitial atoms, and foreign atoms created by transmutation. The latter two types of lattice defects are known to impede the slip process. The effect of vacancies is not well understood, although it is believed that their effect on slip is small. At this time, the most that can be said with certainty is that the effect of irradiation has been to produce lattice defects which impede slip, or in other words, which increase the critical resolved stress required for slip.

On the basis of experimental results obtained with other metals,^{3,4} the transition temperature for irradiated molybdenum in the notched-bar test is probably well above +70°C. Furthermore, since service parts usually contain notches, the transition temperature for these parts would probably also be well above +70°C.

It has been shown for other materials that the irradiation hardening and increase in yield strength is less for specimens irradiated at higher temperatures.^{11,12} This effect is assumed to arise because the lattice vacancies and interstitial atoms produced by the neutron irradiation diffuse out of the lattice at a higher rate because of increased atomic mobility at the higher temperature. Consequently, it should be possible to irradiate a given metal at a temperature at which the annealing rate equals the defect production rate, and there is no radiation hardening. For molybdenum this should mean that the radiation embrittlement decreases as the temperature of the material during the irradiation is increased. Some results reported for molybdenum¹³ indicate that the temperature at which there would be no embrittlement will probably be quite high. These results showed that molybdenum, which was irradiated at 400°C for an estimated 3×10^{20} thermal nvt, increased in hardness by approximately 47 Brinell numbers. This hardness increase was somewhat greater than that for the material reported here. The reason is not fully understood at this time, but it is believed to be due to the fact that the material was of lower original hardness. It has been generally observed that, for a given metal, the lower the original hardness, the greater will be the radiation hardening. Because of the rough correlations between hardness, yield strength, and transition temperature, these results indicate that the rate of defect production in molybdenum at 400°C exceeds the annealing rate and that the material is embrittled even at this temperature.

The effect of operating molybdenum reactor parts at a high temperature should be beneficial in two ways: first, the rate and amount of radiation embrittlement should be reduced; second, the part should be well above the transition temperature and not subject to brittle fracture. Hence, while the

part is operating at the high temperature, the danger of brittle fracture should be small; however, if the temperature is lowered considerably, as during a shutdown, the danger will once again be present.

In conclusion, the results clearly show that commercially pure molybdenum is an unsafe material for low-temperature (below 100°C) use in load-carrying reactor components, in that it is subject to brittle fracture. The results also indicate that it may be possible to use this material in reactors provided that it is continuously operated at a relatively high temperature.

APPENDIXTHE TRANSITION TEMPERATURE OF METALSA. Behavior of Metal Single Crystals under Load¹⁴

A normal metal is an aggregate of many grains or crystals. Therefore, a study of the behavior of single metal crystals under load is helpful in understanding the behavior of a normal polycrystalline metal under load.

When a metal single crystal is stressed monotonously in tension it distorts elastically at first, after which one of the following three events occurs:

1. The crystal deforms plastically by a slip mechanism;
2. The crystal deforms plastically by a twinning mechanism;
3. The crystal fractures suddenly by a cleavage mechanism.

It is found that, if slip or twinning occurs, it is necessary to increase the stress on the crystal in order to cause further plastic deformation. Crystals seldom deform by twinning alone. Usually the twinning process deforms the crystal in such a way as to make it possible for the crystal to slip easier. Eventually the crystal will be deformed to such an extent that it can no longer slip or twin, and it fractures by either a shear or cleavage process. Such a crystal is considered ductile.

On the other hand, a crystal which fractures by cleavage immediately following some elastic deformation is considered brittle. Crystals which show only a very small amount of plastic deformation prior to fracture are also considered brittle.

The large majority of metals fall into three crystallographic systems; namely, face-centered cubic, body-centered cubic, and hexagonal close-packed. In each of these systems there are specific planes of atoms and specific directions on which slip, twinning, or cleavage can occur. These are called slip systems, twinning systems, and cleavage systems, respectively. The experimental evidence indicates that, with each of the three mechanisms, there is associated a critical resolved stress. That is, if the applied stress is resolved into components acting normal and tangent to each slip, twinning, and cleavage system, each process occurs when a constant or critical resolved stress is reached. Hence, when a given crystal is loaded, the resolved stresses on the various atomic planes increase until one of the three critical stresses is reached, at which time the crystal either deforms plastically or fractures. It is also found that when slip does occur, the slip systems rotate

to a more favorable position for further slip. In both body-centered cubic and hexagonal close-packed crystals, all three processes of deformation have been observed; however, in face-centered cubic crystals only the slip process has been observed.

There are undoubtedly many factors that have some influence on the critical resolved stresses required for slip, twinning, and cleavage. Little is known concerning factors influencing the latter two; however, it is known that the following factors raise the critical resolved stress required for slip:

1. A decrease in testing temperature
2. An increase in the rate of load application
3. An increase in the amount of plastic deformation prior to the test
4. An increase in alloy content

By making use of the knowledge of factors influencing the critical stress for slip, it is possible to change the behavior of single crystals under load from ductile to brittle. For example, if a hexagonal crystal with suitable crystallographic orientation with respect to the load axis is stressed in tension at room temperature, the critical stress for slip will be reached first and the crystal will deform plastically by both slip and twinning. The load-elongation curve will be similar to that shown in Figure 8. If an identical crystal, having the same orientation as the first, is stressed in tension at a lower temperature, the critical resolved stress required for slip will be raised above that required for cleavage and the crystal will fracture by cleavage. The stress-strain curve will be as shown in Figure 9. Since the area under the stress-strain curve is a measure of the energy required to fracture the crystal, it can be seen that relatively little energy is required to fracture the crystal when it does not undergo slip or twinning. If enough identical crystals are tested at various temperatures, a graph of the energy required to fracture the crystal versus temperature can be drawn, and it will be similar to that shown in Figure 10.

It can be seen from this figure that there is a critical temperature, called the transition temperature, below which the crystal is brittle for the particular test conditions, and above which it is ductile. The transition temperature is not characteristic of the material; rather, it is characteristic of the test conditions. This transition from plastic to brittle behavior has been observed for some hexagonal close-packed, body-centered cubic, and rhombohedral crystals, but not for any face-centered cubic crystals.

B. Behavior of Polycrystalline Metal Aggregates under Load

At present, only the qualitative results from single crystal experiments can be applied to the behavior of polycrystalline metal aggregates. The primary reason for this can be attributed to the presence of grain boundaries, which are in essence the meeting places of the various grains or crystals. Another possible reason is the presence of phases other than the one of major interest, but this will not be considered here.



FIGURE 8

SCHEMATIC LOAD-ELONGATION CURVE FOR A HEXAGONAL METAL SINGLE CRYSTAL WITH IRREGULARITIES DUE TO TWINNING. TEST CONDUCTED AT ROOM TEMPERATURE

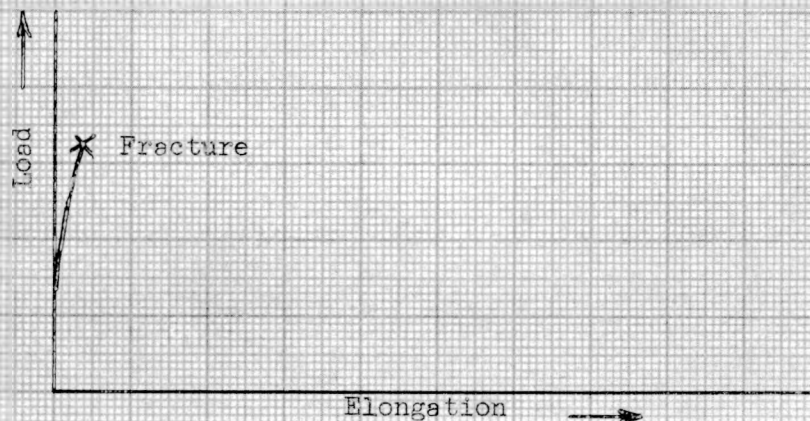


FIGURE 9

SCHEMATIC LOAD-ELONGATION CURVE FOR IDENTICAL CRYSTAL AS SHOWN IN FIGURE 8. TEST CONDUCTED BELOW ROOM TEMPERATURE.

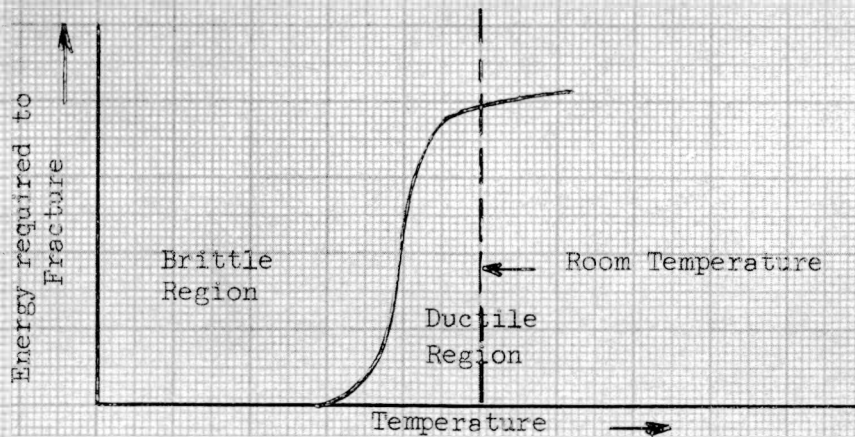


FIGURE 10

RELATIONSHIP BETWEEN TEMPERATURE AND ENERGY REQUIRED TO FRACTURE SINGLE HEXAGONAL CRYSTALS OF IDENTICAL ORIENTATION (SCHEMATIC)

The presence of neighboring grains and the associated grain boundaries act as a restraint to the deformation of a given grain, and for this reason introduce another important factor which influences the critical stress required for slip and which may also influence the critical stresses required for twinning and cleavage. The restraining influence of grain boundaries was shown by Chalmers¹⁵ who experimented with tin bi-crystals. His results showed that the presence of grain boundaries raised the critical stress required for slip in an amount dependent upon the relative orientations of the two crystals. The critical stress was a minimum when the crystals had nearly the same orientation, and was a maximum when the crystal orientations differed the most, but in all cases was higher than that for a single crystal.

When polycrystalline metals are stressed, each individual grain is also stressed. Since there are a multitude of grains randomly oriented, the resolved slip, twinning, and cleavage stresses vary from grain to grain. Whenever one of the critical resolved stresses is reached in some grain, it behaves accordingly. If the first critical resolved stress to be reached is that for slip or twinning, the grain deforms plastically, the slip systems rotate into more favorable position with respect to the applied load, and the critical stress for slip or twinning is raised in this grain as a result of strain hardening. This grain will continue to deform plastically until a critical resolved stress is reached in some other grain which then deforms. If the first critical stress to be exceeded in some grain is that for cleavage, the grain fractures. As a result, the stress on the other grains is increased and these behave according to which critical resolved stress is reached first.

If the large majority of the grains in the polycrystalline metal slip or twin, the metal can be deformed plastically before fracture and the metal is considered ductile. If, however, the majority of grains fracture by cleavage with little or no slip or twinning, the material is considered brittle. Hence, the qualitative performance of the polycrystalline metal reflects the performance of the single crystal.

All common face-centered cubic metals show considerable ductility under all conditions of testing. However, many metals of the hexagonal close-packed or body-centered cubic systems may be either ductile or brittle, depending on the test conditions. If metals from the latter two systems are tested in tension with temperature as the only variable, it is found, as in the case of single crystals, that there is a transition temperature below which the metal is brittle and above which it is ductile. As in the case of single crystals, the transition temperature for a particular metal is characteristic of the test conditions and not of the metal.

There are many factors that influence the value of the transition temperature, and these will be discussed using concepts advanced by Ludwig.¹⁶ Figure 11 is a schematic diagram of the variation in both the flow stress (or yield stress) and the fracture stress of a given metal with temperature. The yield or flow stress is analogous to the critical resolved stress for slip or twinning in single crystals. It is usually defined as the stress necessary to produce a fixed, measurable amount of plastic strain in a test specimen.

The yield stress in a polycrystalline metal, therefore, is reached after the critical stresses have been exceeded and slip or twinning has occurred in many individual grains. The fracture curve is analagous to the fracture stress for single crystals. It is the stress at which the specimen fractures, and as such it is the stress at which all of the individual crystals fracture.

At this time, it is possible to obtain experimentally only parts of the curves illustrated in Figure 11, and these are indicated on the diagram by the broken lines. For this reason the curves are schematic. According to this diagram, if a metal is tested at a temperature above the intersection of the two curves, the flow curve is first reached and the metal deforms plastically. The stress necessary to produce further plastic deformation increases because of strain hardening and eventually the material fractures because the stress required for fracture is less than that required for flow. On the other hand, if the metal is tested at a temperature below the intersection of the curves, the fracture stress is reached first and the metal immediately fractures in a brittle fashion. The intersection of the flow and fracture curves, therefore, is the transition temperature for this particular set of testing conditions.

If, by some means, the relative position of the flow curve is altered with respect to the fracture curve for a given metal, there will result a change in the transition temperature. Although it is not possible at this time to determine completely either the flow or fracture curves, and to evaluate fully the effect of many test variables on them as well as the transition temperatures, the evidence available indicates that the fracture stress curve is relatively stable as compared to the flow stress curve. Experiments have shown that there are many variables which do shift the flow curve as well as the transition temperature. The most important of these, which raise the transition temperature, are as follows:

1. Increasing stress triaxiality
2. Increasing the rate of loading
3. Increasing the amount of pre-strain
4. Strain aging
5. Increasing the grain size.

The first factor is considered the most important to this discussion, since it is a condition which exists in stressed members if there are any notches, nicks, holes, angles, etc., either accidental or intended. It has been shown⁴ for high-purity iron that the transition temperature in tension is approximately -170°C , whereas it is 15°C in a notched bar impact test in which a triaxial stress system exists. The notch effect is quite pronounced and is considered one of the causes of the serious failures of welded ships that occurred during World War II.¹⁷ An analysis of these failures has shown that

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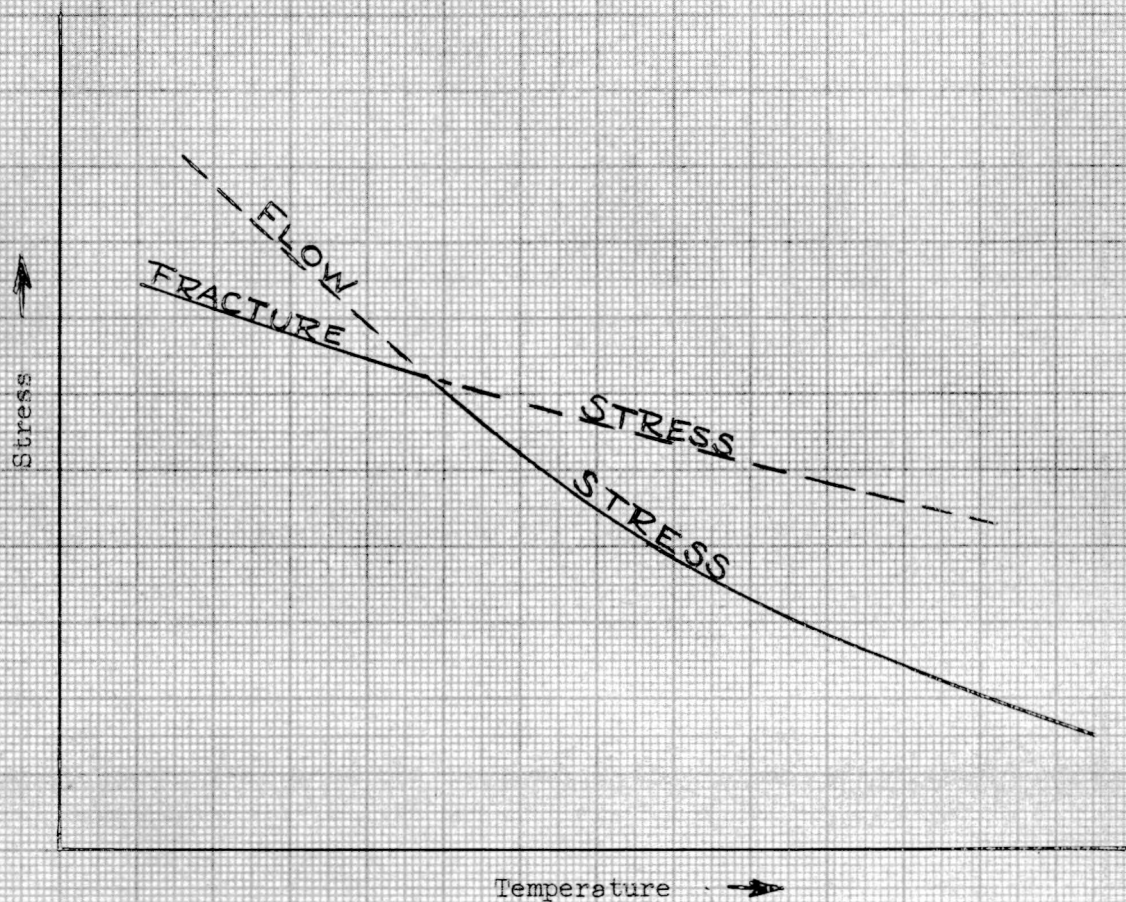


FIGURE 11

SCHEMATIC DIAGRAM OF THE VARIATION IN BOTH THE FLOW
STRESS AND THE FRACTURE STRESS OF A GIVEN METAL WITH
TEMPERATURE. (after Ludwig¹⁶)

all of the failures in these ships originated at some type of notch. It has also been shown that the transition temperature in a notched-bar impact test was higher in the material in which cracks originated, than in the material where the cracks terminated.

Hence, it must be concluded that metals which exhibit both brittle and ductile behavior, depending on the test conditions, must be employed with caution, since many factors influence the performance of these metals during service.

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